RESEARCH DEPARTMENT

THE MEASUREMENT OF MODULATION NOISE ON MAGNETIC TAPES

Report No. C-090

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1. INTRODUCTION.

An important factor determining the suitability of a given magnetic tape for use in the broadcasting system is the level of modulation noise experienced when the tape is recorded. The level of background noise when the unrecorded tape is passing the reproducing head may be negligible but when the same tape is "modulated" (i.e. recorded) an increase of background noise may occur which is audible when the recorded signals are being reproduced but which is still not audible in "unmodulated" parts of the tape. Various mechanisms for the effect can be postulated and the noise components fall into four categories as follows:

(a) those arising in the fundamental magnetising process and depending on the magnetic domain structure of the medium,

(b) those arising from amplitude modulation of the signal due to manufacturing imperfections of the magnetic tape,

(c) those arising from amplitude modulation of the signal due to variations in the tension of the tape over the heads, and

(d) those arising from frequency modulation of the signal, due to imperfections of the tape transport system of the machine in conjunction with certain mechanical properties of the tape such as the coefficient of friction of its surface and its modulus of elasticity. This may be otherwise described as "flutter" or "wow".

In the field of professional recording machines it must be assumed that modulation noise components in categories (c) and (d) will be small and in any event their magnitude is controlled by other tests and specifications regarding speed constancy. Thus in selecting tapes for use on professional equipment the tests carried out are designed to determine the magnitude of components falling in categories (a) and (b). The result obtained is largely independent of a good quality machine on which the tape is tested providing it has an otherwise acceptable noise level and that its frequency response is in accordance with agreed standards.

2. AMPLITUDE MODULATION IN THE MAGNETIC TAPE.

The magnetic material forming the recording medium, which is coated on to the plastic backing, consists of crystals which vary in size, to a greater or lesser degree and which may, or may not, be randomly orientated, according to the conditions of manufacture. These crystals, according to their size and composition, will constitute one or more magnetic domains. In all cases it follows that the variation of magnetisation within any one wavelength along the tape cannot take place smoothly and continuously but must occur in a series of discrete steps or jumps. Thus a fundamental noise must be superimposed on the wanted part of the signal which results from the mean variation of magnetisation.

The three principal manufacturing imperfections, which probably give rise to the major part of modulation noise, are:

(a) lack of smoothness in the tape surface,

(b) variation of coating density, i.e. "packing factor", due to the variations in particle size and agglomeration, and

(c) variation of thickness of the tape coating.

Lack of smoothness in the surface of the tape causes a variation in the effective separation of the magnetic coating from the pole-tips of the magnetic head. If this variation is due to particles projecting from the surface of the tape, or to non-uniformity of particle size in the coating mixture, then the separation may be expected to vary in a random manner and hence the effects of separation will be random in nature. The effect of separating the magnetic medium from the recording head is to lower the recording field strength so that there will be a change in the recorded intensity of the signal. The magnitude of this change will depend on the bias and recording field employed and on the head design, but at high frequencies it will generally be small in comparison with the equivalent effect in the reproducing process. It may be shown that the output from a reproducing head is proportional to the factor

$$\exp\,(-2\pi d/\lambda)$$

where d is the effective separation and λ the recorded wavelength being reproduced. Separating a recorded signal of wavelength λ from the reproducing head by a distance equal to λ will, therefore, create a drop in reproduced level of about 55 dB. Now with modern tape recording technique it is possible to record the whole audio-frequency range at tape speeds of the order of 15 in./sec (38·1 cm/sec) so that extremely short wavelengths may occur in a high-quality recording. Varying the separation between the recorded tape and the reproducing head may then create very large amplitude modulations of the signal of an amount depending on the wavelength being reproduced. When the signal is absent there is no output present to be amplitude modulated and the system may appear quiet. These separation variations may, of course, be reduced by polishing the tape surface but this process will not reduce the modulation noise due to variations of density or packing within the coating. Changes in the tension of the tape across the head will also vary the effective separation and produce amplitude modulation. However, as noted previously, this defect of the machine should not be allowed to influence acceptance tests for magnetic tape and it must be assumed that the test machine is of adequate quality to make this contribution negligible.

Variations in the thickness of the magnetic coating may be due to lack of smoothness in the surface of the base material and to imperfections in the spread of the coating during manufacture. At longer wavelengths the thicker the coating the greater is the surface flux emanating from the recorded tape and, hence, on reproduction, the greater the voltage induced in the reproducing head.

Now the discussion of the effects of separation between head and medium indicates how profound is the influence of this factor on the reproduction of shorter wavelengths. Thus, although a tape may be recorded with almost equal intensity throughout its thickness, the effect of the various layers of the coating on the reproducing head depends on their separation from the head surface. At very short wavelengths only recorded layers near the surface have an appreciable effect on the reproducing head, whilst at very long wavelengths almost the whole thickness of the tape contributes to the reproduced signal. It follows that the result obtained in a modulation noise test of any given tape will depend on:

(i) the test frequency employed, and

(ii) the nature of the imperfection in the tape.

Lack of modulation noise at 10 kc/s test frequency would indicate surface smoothness but would give no indication of the quality of the base——only a test at low frequencies could indicate this. On the other hand, making a test with only very low test frequencies would indicate the constancy, or otherwise, of coating thickness and the condition of the base material surface, but might not give a correct indication of the condition of the coating surface except where this had fairly gross defects. Clearly, tests at both low and high frequencies are required to give a complete picture of the tape quality. However, two trends are now observable in magnetic recording, namely, the introduction of new plastic base materials of improved quality and the increasing use of lower tape speeds which results in shorter wavelengths on the tape. The first trend will undoubtedly diminish the incidence of noise due to the base imperfections and the second will increase the relative importance of the higher frequency modulation noise test. It is probable, therefore, that the latter will become increasingly valuable as a check of tape quality.

3. METHODS OF MODULATION NOISE MEASUREMENT.

One method of measuring modulation noise has been in use for some time as one of the acceptance tests for tapes supplied by manufacturers. In this a small direct current is fed to the recording head, together with the normal bias current, and the resultant noise is measured in the reproducing head. Noise voltages are induced in the reproducing head as the direct flux linkage with it changes, either as a result of variation in the base surface or coating thickness, or of the medium moving backwards and forwards from the head surface due to poor surface smoothness of the medium. In this context the direct current can be considered as representing zero frequency so that the results obtained are more an indication of variations of coating thickness and of the conditions of the base material surface than of the quality of the coating surface, unless the latter is very rough. Clearly the information from this test should be supplemented by the results of another designed, more specifically, to test coating surface condition, i.e. by a measurement carried out using a test frequency which produces suitably short wavelengths on the tape. The next paragraph describes such a standard measurement which can, if required, be included in the acceptance test procedures. The principle of the measurement is to feed a test tone into the recording machine, record it on the tape under examination, and measure the amplitude modulation which results on reproduction, using a calibrated detector for the measurement.

4. MEASUREMENT OF AMPLITUDE MODULATION IN TEST TONES.

Tones of 5 kc/s and 10 kc/s are employed in making the measurement, the former being suitable for testing modulation noise at a tape speed of 7½ in./sec, and the latter at a tape speed of 15 in./sec. When the test tone is reproduced from the machine the quantities of interest are the mean reproduced amplitude and the percentage modulation represented by the various negative and positive peaks. A block schematic diagram of the measuring chain is shown at Fig. 1, from which it will be seen that the chain contains a linear diode detector, a low-pass filter of suitable cut-off frequency and a meter which is used to read some measure of the modulation envelope. If a peak-reading meter is used to measure the positive and negative peaks of the modulation envelope it may be calibrated in terms of percentage peak modulation. Alternatively, in place of the peak-reading meter, some device such as a thermal meter may be employed to read the r.m.s. value of the modulation. The reading device most suitable for acceptance testing will be discussed later. The circuit diagram of the linear diode detector is shown in Fig. 2. In an ideal linear diode detector the output voltage developed across the diode load resistance contains a steady component and a component which is an exact replica of the modulation envelope, both components being proportional to the signal amplitude and the detector efficiency. The average diode current is thus a measure of mean signal amplitude and this quality may be measured by a suitable microammeter included in the diode load circuit.

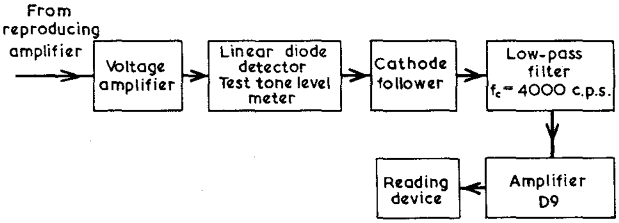
From reproducing amplifier
Voltage amplifier
Linear diode detector Test tone level meter
Cathode follower
Low-pass filter f_c = 4000 c.p.s.
Amplifier D9
Reading device

Fig. 1 - Block schematic diagram of measuring chain

It is, of course, essential to make sure that the frequency characteristic of the diode detector circuit is suitable for the range of frequencies involved in the modulation noise measurement. The combined diode detector and filter characteristic, which is shown in Fig. 3, is for practical purposes level up to a frequency of 1500 c/s. The relative higher frequency content of the modulation noise from a typical E.M.I. H.50 tape, measured by means of a selective amplifier, is shown in Fig. 4. It will be observed that the higher frequency content falls rapidly above 100 c/s and no appreciable energy above 1000 c/s appears to be present. The higher frequency characteristic of the diode detector is thus quite suitable for measuring modulation noise, assuming that an E.M.I. tape is fairly typical.

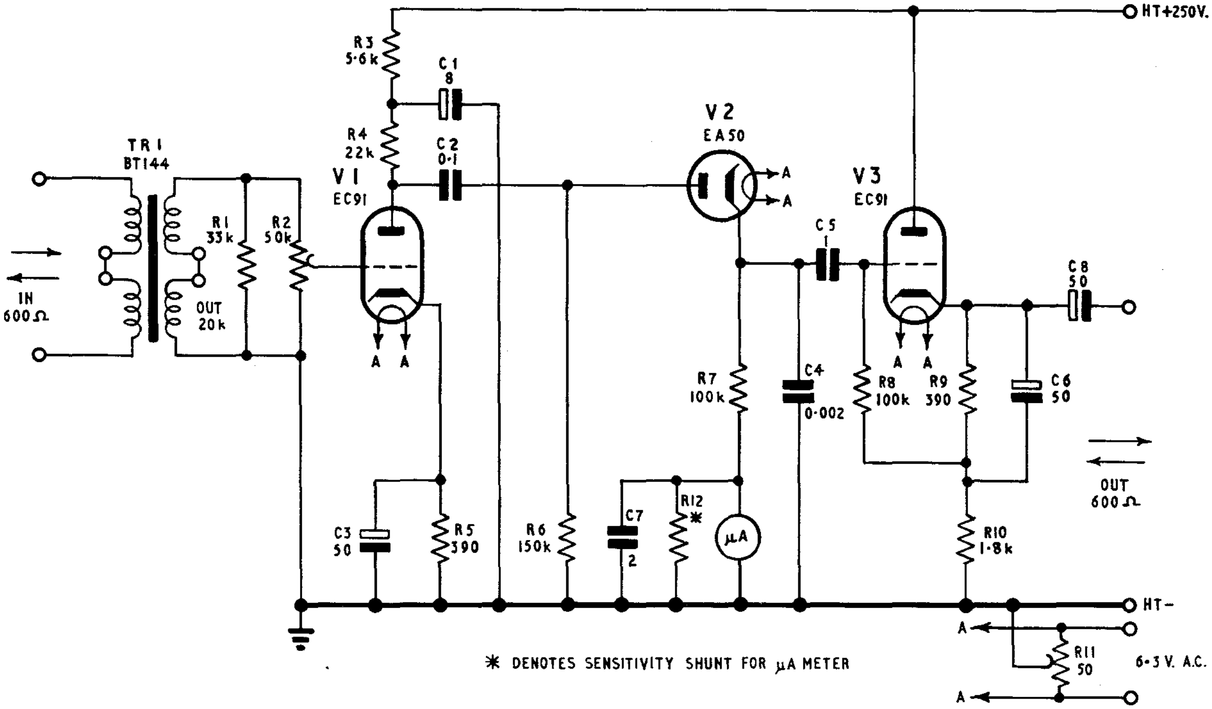

Fig. 2 - Linear diode detector

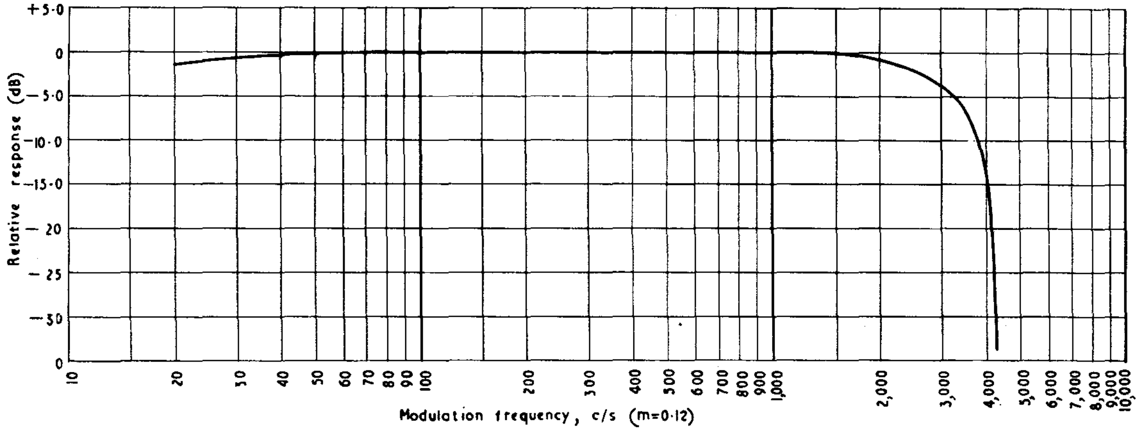

Fig. 3 - Modulation frequency response of linear diode detector with low pass filter

5. THE NATURE OF MODULATION NOISE.

5.1. Statistical Analysis of Noise Current.

When a peak-reading meter is used to indicate the amplitude modulation from a tape, it is observed, not unexpectedly, that the peaks obtained vary in magnitude in what appears to be a random manner. Such a signal is difficult to interpret visually and it is not possible for the observer to know the importance he should attach to larger peaks in relation to their frequency of occurrence. To resolve this difficulty it is first necessary to establish the exact nature of the modulation noise.

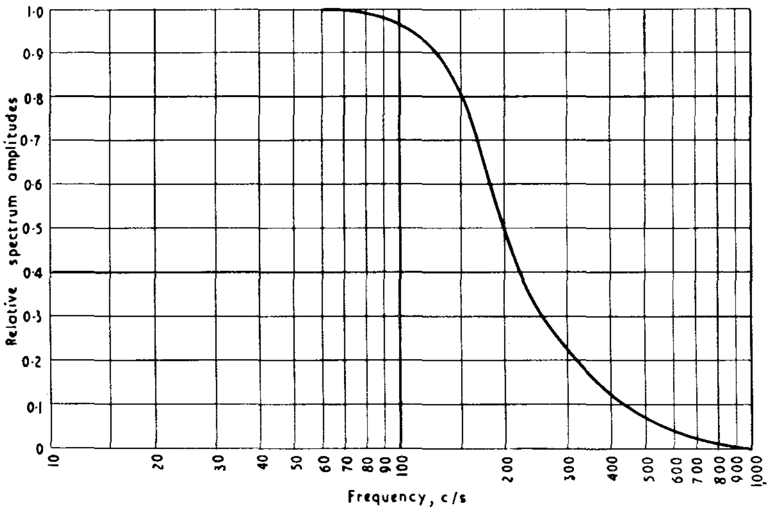

Fig. 4 - Frequency spectrum of modulation noise from typical magnetic tape (test tone - 10 kc/sec)

The continuous amplitude-modulation envelope provided by a typical E.M.I. type H.50 tape was, therefore, obtained for analysis by indicating the instantaneous amplitude as the position of a spot on the *y*-axis of a cathode-ray oscilloscope, without the time-base in action, and recording this vertical position continuously on a moving photographic film. The movement of the photographic film then provides the *x*, or time axis. The variation of amplitude of the modulation envelope over a period of just under one second is shown in the record of Fig. 5. This recording represents, in effect, the noise current flowing in the output of the detector. To determine the properties of this noise current the record is analysed by a method[1] which has been previously applied to phenomena of this nature, as follows with reference to Fig. 6. In its simplest form the method entails drawing a series of horizontal lines through the trace at regular intervals of amplitude. The number of intercepts at each amplitude level (above some arbitrary zero) is then counted, using any suitable observing technique, and the results are plotted in the form of a graph showing the number of intercepts against amplitude level. If the noise current is random this process amounts to measuring its amplitude at a great many random instants. This curve represents what may be called the distribution of amplitudes in the noise current and its shape will indicate the statistical properties (if any) of the signal. The

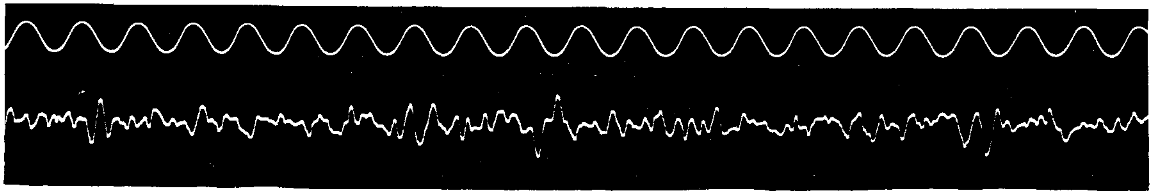

Fig. 5 - Photographic record of demodulated amplitude envelope of 10 kc/s tone recorded on, and reproduced from, an E.M.I. H.50 tape

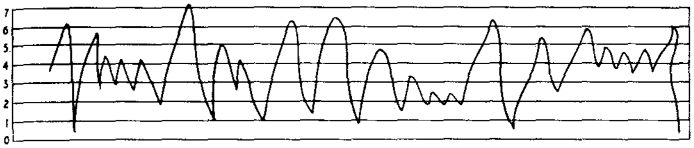

Fig. 6 - Method of analysing complex modulation envelope

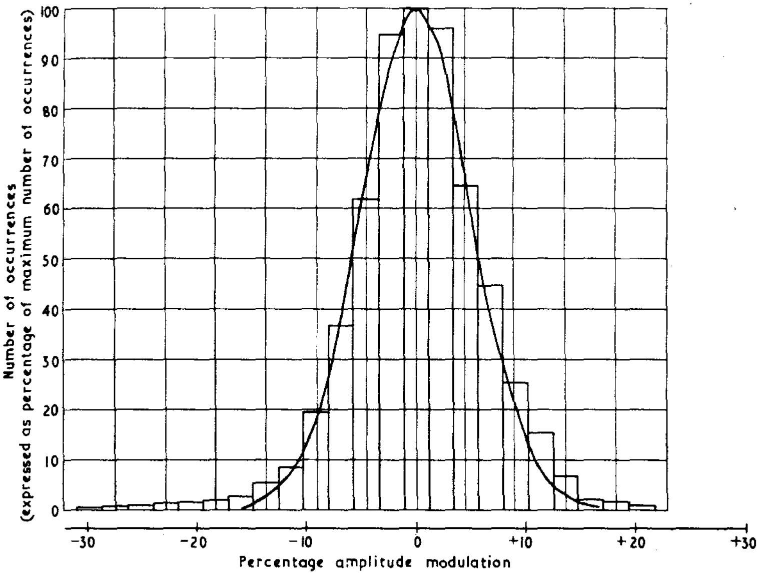

Fig. 7 - Distribution of amplitudes in modulation envelope of recorded 10 kc/sec tone

distribution of amplitudes in terms of percentage amplitude modulation, obtained from the record of Fig. 5, is shown in Fig. 7, in the form of a histogram. It will be observed that the distribution is almost symmetrical, apart from a small "tail" of extreme negative amplitudes which represent large drops of the original modulated signal. On the assumption that the distribution is, to a good approximation, symmetrical, a normal curve has been fitted to it and this curve encloses about 95% of all the readings. Thus the modulation envelope from the tape is largely random in nature, and the close approximation to a normal curve indicates that the probability p, of any particular fluctuation having an amplitude lying between R and $(R + \delta R)$ is given by $dR/(2\pi\tau_0)^{\frac{1}{2}}.\ \exp -R^2/2\tau_0$ where τ_0 is a constant, depending on the power spectrum, $w(f)$, of the fluctuation current, given by

$$\tau_0 = \int_0^\infty w(f)df.$$

Actually τ_0 is also the mean square value of $R(t)$ i.e. the r.m.s. value of $R(t)$ is $\tau_0^{\frac{1}{2}}$. These findings will give an indication of the manner in which the modulation envelope should be observed for test purposes. Strictly it would be desirable to check that this distribution is stationary in time, i.e. that the mean or other constants of the distribution do not vary appreciably with the position of the length analysed in the whole record. This could be checked by analysing a number of equal lengths of photographic trace taken from various parts of a long record and comparing the resultant distributions. The process of manufacture of tape, however, makes it unlikely that a modulation envelope would be obtained which was random in amplitude and not, at the same time, statistically stationary in time. Here, the question has not been pursued for, as will appear later, the measuring chain to be proposed for acceptance tests will indicate correctly even if amplitude modulation of well-defined frequency is present. This is important because such modulation may be met, in practice, emanating from the recording machine itself, as distinct from the tape.

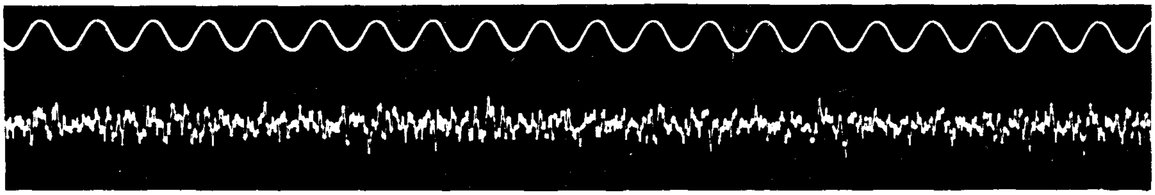

Fig. 8 - Photographic record of demodulated amplitude envelope of a 10 kc/s tone modulated by "white" noise

5.2. Check of the Measuring Chain.

In order to verify that the measuring chain, the photographic recording technique and the subsequent analysing process were not in any way distorting the result, the whole chain was checked with a true noise voltage obtained by feeding the detector with a 10 kc/s tone modulated by white noise. The modulation levels in this and the tape case were adjusted to equality on the basis of equal r.m.s. value of noise current in the final output, as indicated by a thermocouple system. The photographic trace obtained in this case is shown in Fig. 8 and it was analysed by the method described previously. A histogram of the distribution of amplitudes obtained, together with a fitted normal distribution, is shown in Fig. 9. It is interesting to note that the very large negative amplitudes shown in Fig. 7 are absent in Fig. 9. It is possible in the tape case that these large negative amplitudes resulted from "drop-outs", i.e. small microscopic areas where magnetic particles were almost completely absent, or where large "foreign bodies", such as dust, may have taken the tape out of contact with the heads.

5.3. General Measurement of Fluctuation Spread.

To obtain an indication of the manner in which the modulation noise envelope from the tape can be observed for general test or standardisation purposes, it will be of interest to compare the distributions of Figs. 7 and 9 in rather more detail. Inspection of Figs. 7 and 9 indicates that, apart from the negative "tail" of the tape noise distribution, which is believed to be due to drop-outs, the spread of the two sets of fluctuations is very similar. Now the statistical constant of such a distribution which is a measure of spread is its standard deviation, i.e. the root mean square deviation from the arithmetic mean. The computed standard deviations of the distributions of Figs. 7 and 9 (in arbitrary units) are 0·1345 and 0·1213 respectively, i.e. with their r.m.s. values adjusted to equality by means of a meter the graphically computed standard deviations differ only by some 10%. A meter measurement of the r.m.s. or standard deviation, therefore, appears quite adequate.

5.4. Discussion.

It should be noted that the rates, i.e. the average number of fluctuations occurring in unit time, in the two cases considered above, is very different. This may be accounted for by the differing degree to which the two noise currents analysed are spectrally restricted. The spectral restriction of the modulation noise from the tape is indicated by the selective amplifier measurements shown in Fig. 4, and that of the white noise by the frequency response of the linear diode detector shown in Fig. 3. In each case the situation is equivalent to passing white noise of

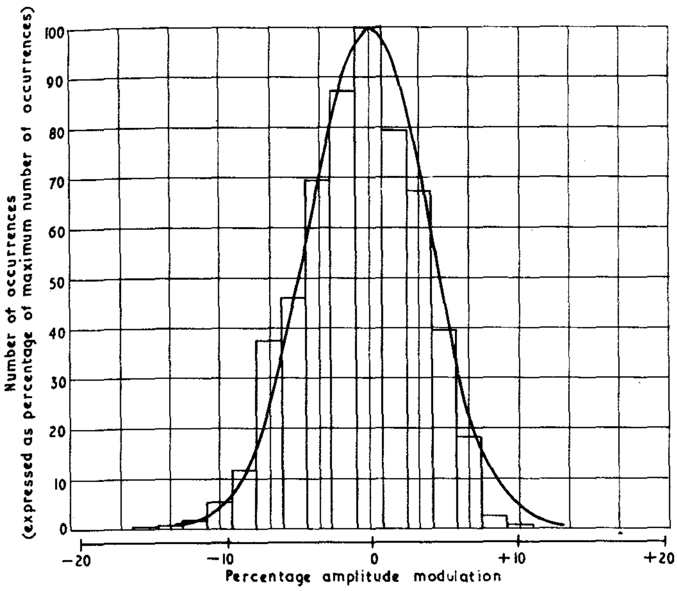

Fig. 9 - Distribution of amplitudes for white noise amplitude modulated 10 kc/sec test tone

infinite bandwidth through a low-pass filter. The low-pass filter in the tape case is a mechanical one arising from such factors as the inertia of the tape to separation from the head, the tape tension, the ability of the tape to stretch, and similar factors. The low-pass filter in the white noise case is the diode detector, this being equivalent (in its turn) to a perfect detector accepting infinite bandwidth followed by a low-pass filter of the cut-off frequency indicated.

Now Rice[2] and others have, in various analyses, represented a noise current as the sum of N independent random vectors by the equation

$$I(t) = \sum_{n=1}^{N} (a_n \cdot \cos \omega_n t + b_n \cdot \sin \omega_n t)$$

where the coefficients a_n and b_n, $1 < n < N$, are regarded as independent random variables distributed about zero according to a normal law. By the central limit theorem a precisely normal distribution of amplitudes is obtained as $N \to \infty$ but in practice even limited values of N (which must be the case for modulation noise) give a close approximation to normality providing the individual coefficients a_n and b_n are normally distributed[3]. This equation represents a Fourier series and the effect of a low-pass filter through which the noise is fed is to restrict the upper value of ω_n approximately to the cut-off frequency of the filter. This does not alter the normal character of the distribution of current amplitudes, either, providing that in the analysing process a correspondingly larger sample is investigated as the bandwidth becomes more restricted. The statistical constants of the normal distribution depend, of course, on the power spectrum of the analysed noise signal, i.e. on the frequency content of the input noise and on the shape of the frequency characteristic of the low-pass filter and rectifier, these factors determining the constant τ_0 previously discussed. In considering the results obtained here it may be concluded that the value of N provided by the various factors producing modulation noise from the tape is large enough to provide a close approach to the normal law, i.e. modulation noise is a true noise in the statistical sense. Thus, an adequate measure of modulation noise may be obtained by measurement only of the r.m.s. value of the noise current, i.e. by measurement of the r.m.s. value of the low-frequency output (that part below the audio carrier frequency) with an r.m.s. or thermal meter of suitable type.

6. THE MEASURING CHAIN AND THE SUBJECTIVE THRESHOLD.

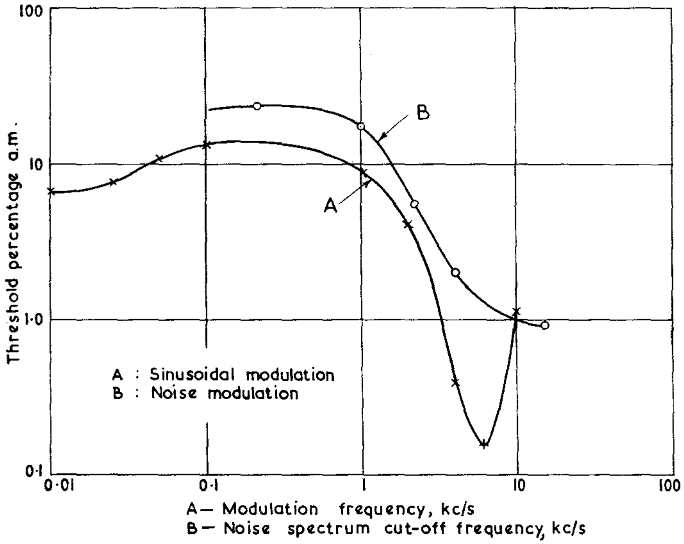

Fig. 10 - Variation of subjective threshold for amplitude modulation of piano programme

The object of making the modulation noise test is to determine whether, in that respect, a given tape is suitable for the recording of high-quality programme. The subjective impression obtained when the modulated or demodulated test tone is heard through a loudspeaker is of interest, but it can give no precise indication of the effect of the tape imperfections on the quality of recorded programme. The subjective effect of amplitude fluctuations on programme has recently been investigated, however, and the results described elsewhere[4]. Two relevant sets of experimental results for amplitude modulation of piano programme were obtained in the course of this work, namely the variation of subjective threshold (A) with frequency of sinusoidal modulation and (B) with the upper cut-off frequency of white noise modulation spectrally restricted by a low-pass filter. The experimental conditions in the latter are, therefore, equivalent to the "tape noise" modulation or "white noise" modulation conditions analysed here. The piano was chosen for the experiments as being very sensitive to the undesired pitch and amplitude fluctuations which occur in recording systems, thus providing a critical medium on which to establish permissible tolerances in practical systems. The variation of subjective threshold for these two types of amplitude modulation of of piano programme, as found in the experiments, is reproduced in Fig. 10. If the modulation envelope from the tape is to be correctly related to the effect which the imperfections causing it would create in recorded programme, then the measurement should be weighted so as to give relatively greater emphasis to those components of amplitude modulation to which the listener is most sensitive. The measuring chain, should, therefore, include a frequency weighting network having a characteristic which is the inverse of the relevant subjective threshold variation shown in the figure.

7. CALIBRATION OF THE MEASURING CHAIN

Strictly the weighting network introduced should be the inverse of Curve A if the amplitude modulation is predominantly periodic in character and it should be the inverse of Curve B if the amplitude modulation on the tape is predominantly random in character. However, it will be observed that the shape of Curves A and B is almost identical over the frequency range of interest, so that the frequency weighting network can be the same for each case. The function represented by Curve A, however, is everywhere less than that represented by Curve B so that the absolute calibration carried out on the measuring chain would not be the same if the readings obtained had to be related precisely to random or periodic modulation thresholds.

Itis not possible, except by some analysing process such as that described in paragraph 5, to determine whether the modulating signal is predominantly random or periodic so that it would hardly be practicable in general testing to call for a variation of the absolute calibration to suit these two conditions. Therefore, the absolute calibration of the amplitude modulation chain is best related to the threshold variation to which the listener is most sensitive, i.e. to the threshold for periodic amplitude modulations. This will ensure that the apparatus is correct should the modulation envelope from the tape be largely periodic and it will provide an extra insurance in the random modulation case by calling for an absolute standard which is a little more severe than strictly necessary. It will also have the advantage that the same apparatus may be used for modulation noise testing as will be required for the testing of amplitude modulation in recording machines. The measuring chain can then be calibrated in absolute-threshold terms, or in any other agreed standard, by feeding in the test frequency (say 5 or 10 kc/s) from a tone source sinusoidally modulated at a known frequency with a depth of modulation depending on the standard chosen. For example, if the weighting curve which is the inverse of Curve A is adopted, then the depth of modulation in the test tone should be 10% at a fluctuation frequency of 10 c/s, or 16% at a fluctuation frequency of 100 c/s. The indication obtained is then the reading which should not be exceeded, when the modulation from a tape is examined, if the random or periodic amplitude modulation is to be below the threshold of detection.

Referring once again to the discussion in paragraph 5.4 it is still sufficient for a correct result to measure the output of the measuring chain by means of a thermal meter or r.m.s. device. First, in the case where pure modulation noise is obtained from the tape the presence of the frequency weighting network, which takes account of the threshold characteristics of the human ear, does not alter the normal or Gaussian nature of the random noise, but affects only its power spectrum and hence the standard deviation (the constant τ_o previously discussed). The constant τ_o is, in fact, altered to take account of the variation of threshold with the frequency content of the amplitude modulation. Secondly, in the case where a pronounced regular or periodic component is present the indication is still correct, for this component may be regarded merely as another random vector adding to the N random vectors producing the original normal distribution. In fact, of course, the peak value of the periodic component may not vary at all but in this case it may be regarded as a vector whose normal distribution has infinitely small spread.

Alternative to the above argument the result may be deduced at once from the statement of a known statistical theorem that if two independent probability distributions are superimposed, the average value of the squares of the deviations of the new distribution is equal to the sum of the average value of the squares of the deviations of the original distributions.

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